Journal of Power Sources 271 (2014) 614–621

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

Updating United States Advanced Battery Consortium and Department of Energy battery technology targets for battery electric vehicles

Jeremy Neubauer [a,*], Ahmad Pesaran [a], Chulheung Bae [b], Ron Elder [c], Brian Cunningham [d]

[a] National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, CO 80401, USA
[b] Ford Motor Company, 2101 Village Rd, Dearborn, MI 48121, USA
[c] Chrysler Group LLC, 800 Chrysler Drive, Auburn Hills, MI 48326, USA
[d] U.S. Department of Energy, 1000 Independence Ave., Washington, DC 20585, USA

HIGHLIGHTS

- Joint effort of USABC and DOE.
- Technology agnostic approach to identify BEV battery performance and cost targets.
- Resultant targets will drive future battery development.

ARTICLE INFO

Article history:
Received 1 April 2014
Accepted 9 June 2014
Available online 19 June 2014

Keywords:
United States Advanced Battery Consortium
Battery
BEV
Performance target

ABSTRACT

Battery electric vehicles (BEVs) offer significant potential to reduce the nation's consumption of petroleum based products and the production of greenhouse gases however, their widespread adoption is limited largely by the cost and performance limitations of modern batteries. With recent growth in efforts to accelerate BEV adoption (e.g. the Department of Energy's (DOE) EV Everywhere Grand Challenge) and the age of existing BEV battery technology targets, there is sufficient motivation to re-evaluate the industry's technology targets for battery performance and cost. Herein we document the analysis process that supported the selection of the United States Advanced Battery Consortium's (USABC) updated BEV battery technology targets. Our technology agnostic approach identifies the necessary battery performance characteristics that will enable the vehicle level performance required for a commercially successful, mass market full BEV, as guided by the workgroup's OEM members. The result is an aggressive target, implying that batteries need to advance considerably before BEVs can be both cost and performance competitive with existing petroleum powered vehicles.

1. Introduction

Battery electric vehicles (BEVs) offer significant potential to reduce the nation's consumption of gasoline and production of greenhouse gases. However, one large impediment to the commercial success and proliferation of these vehicles is the cost and performance limitations of current battery technology. BEVs on the market today come with a significant cost premium relative to their conventionally powered counterparts, even after significant federal and state purchase incentives are included. In addition, the range of the vehicle is typically restricted by limited battery energy to ~100 miles under optimum driving conditions. That value can fall considerably in the presence of high auxiliary loads, aggressive driving, extremely cold temperatures, or later in life as the battery ages. Furthermore, when a BEV is based upon a platform designed for a conventional powertrain, the volume displacement of the battery necessary to achieve this limited range results in a reduction in the available passenger or cargo volume. Additionally, as it may be necessary to modify the vehicle chassis to support the large mass of the batteries due to their low specific energy, which adds additional cost to the BEV equivalent.

Improvements in battery technology have the capacity to resolve all of these issues. Accordingly, the Department of Energy (DOE), the United States Advanced Battery Consortium (USABC), and others are directing significant resources towards the development of batteries for BEVs. For example, the DOE has initiated its EV Everywhere Grand Challenge [1] to accelerate BEV

* Corresponding author. Tel.: +1 720 989 1919.
E-mail addresses: Jeremy.neubauer@nrel.gov, jeremy.s.neubauer@gmail.com (J. Neubauer).

http://dx.doi.org/10.1016/j.jpowsour.2014.06.043
0378-7753/

advancement, with a heavy focus on advanced battery technology. In partnership with DOE, the USABC also sets its own battery technology targets to drive developments in the industry. However, as of 2012, the USABC's working BEV battery technology targets were more than 20 years old [2], and documentation providing insight into their development was exceptionally scarce. In light of significant developments in the automotive markets since the last target setting activity and recently increased efforts to deploy BEVs, there is motivation to develop an updated set of BEV battery technology targets.

Consequently, in 2012, the DOE and USABC jointly set out to create a new set of battery technology targets for BEVs. It was desired that the targets be designed to deliver a BEV capable of broad market success if achieved. To achieve this end, the resources of the National Renewable Energy Laboratory (NREL) were leveraged to supply detailed technical analysis, guided by the insight of the USABC's vehicle OEM members on consumer requirements and future vehicle and battery technology trends. Herein, we document this process of updating these battery targets as well as communicate our results.

2. USABC target setting analysis

The objective of this analysis is to identify battery available energy, mass, volume, cost, discharge power, and charge power requirements that will enable broad commercial success of BEVs if the requirements are achieved. Our approach to achieving this objective begins by first specifying the relevant vehicular level performance requirements necessary for commercial success; namely, acceleration and range. Next, we select a vehicle platform with broad market appeal and define its mass and aerodynamic properties using forecasted values for our timeframe of interest. At this point we calculate the required energy and power to meet our range and acceleration targets, then analyze charge and discharge power requirements using vehicle simulation software. Finally, we calculate available battery mass and volume, followed by allowable battery cost to provide cost-parity with a comparable conventionally powered vehicle. All of these steps are detailed in the sections that follow.

2.1. Defining vehicle performance

Two factors of BEV performance are relevant to this study: acceleration and range. These two metrics will have direct impact on the required battery energy and power requirements, and indirectly affect battery mass and cost (considering the mass and cost of the necessary motor and power electronics).

To define an acceleration requirement, we first surveyed the OEMs' preference. This yielded a 9 s 0–60 mph time as an acceptable level of performance. We then simulated a BEV in ADVISOR [3] with this level of performance to 2154 real-world vehicle records [4]. We found that this vehicle was capable of achieving the vehicle speed histories within 1 mph 97.6% of the time across all records. Based on this result, we elected to proceed with the 9 s 0–60 mph acceleration time on the basis that such a vehicle is capable of meeting the dynamic requirements of many drivers.

Defining necessary vehicle range is a more difficult task. If a comprehensive data set on consumer driving habits was available, a complex techno-economic analysis could provide insight into the selection of a cost-optimal range. Such a data set must provide distance and timing information of each trip taken by an individual driver to enable the calculation of vehicle utility, while spanning no less than 365 continuous days to account for seasonal effects. A large number of diverse drivers must also be addressed, to account for variation in driving habits with geography, occupation, age, sex, and other relevant demographics. Further, as vehicle purchase decisions are not generally made on a purely economic basis, consumer choice factors must also be brought into play, further complicating identification of an optimal range for our BEV.

As the necessary data and tools to make an optimal range selection were not available to the authors (nor do they exist, to our knowledge), a more qualitative approach was necessary. We first narrowed our scope to a minimum range of 100 miles, on the justification that our target must improve upon the current state of the art; and, a maximum range of 300 miles, anticipating that such a large range would lead to overly ambitious targets. Second, we looked at national fleet utility factors using the 2009 National Household Travel Survey data [5] assuming a once-per-day charging algorithm and that there is always sufficient time to completely recharge the battery. As seen in Figs. 1 and 2, this data set projects that a vehicle with our minimum range of 100 miles would cover 94% of all travel days and 68% of all miles traveled if deployed nationally. Note that increases in range offer a diminishing increase in fleet utility. For example, increasing range from 100 to 200 miles increases coverage by 5% of travel days and 14% of miles; while increasing range from 200 to 300 miles increases coverage by less than 1% of travel days and 4% of miles.

Note that these are fleet utility factors (based on cross sectional drive distance distributions) rather than individual driver or vehicle utility factors (based on longitudinal drive distance distributions). Accordingly, some drivers or vehicles may have very few of their driving needs met with a range of 200 miles, while others may have all of their needs met (and indeed considerably underutilize the vehicle's full capability).

To provide some insight into the fraction of drivers that would achieve a high utility from such a vehicle, we applied a longitudinal data set of 317 vehicles from the Puget Sound Regional Council's Transportation Choices Study (TCS) [6]. This subset of the larger TCS sample was selected for high data quality over a continuous 365 day period. We resolved the data to a sequence of parked-at-home events and home-to-home driving tours. We then calculated 365 day battery state of charge (SOC) and vehicle miles traveled (VMT) histories for each of the 317 vehicles by applying the following two assumptions to this data: (1) the vehicle is charged with a level 2 charger every time the vehicle is parked at home, and (2) if the SOC of the battery is not sufficient to complete a home-to-home tour at the original time of departure, the BEV is not used for that tour. The miles-based utility factor for each vehicle can then be

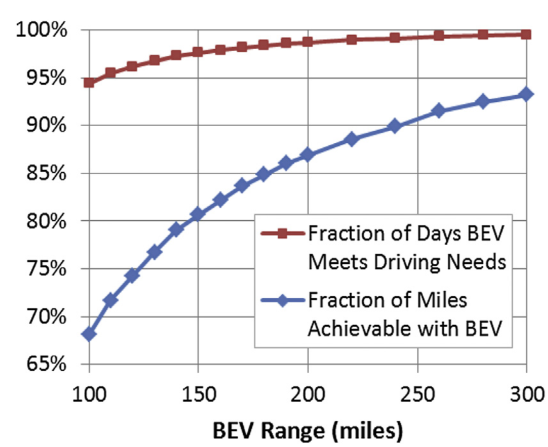

Fig. 1. Days- and miles-based fleet utility factors for BEVs as a function of range based upon 2009 NHTS data.

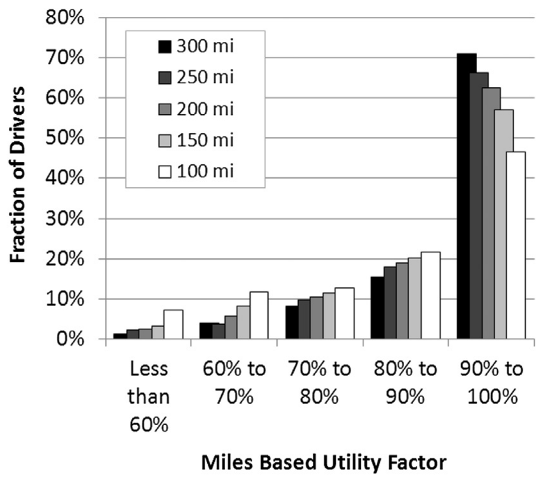

Fig. 2. Histogram of miles-based individual vehicle utility factors for a BEVs of multiple ranges based upon TCS data.

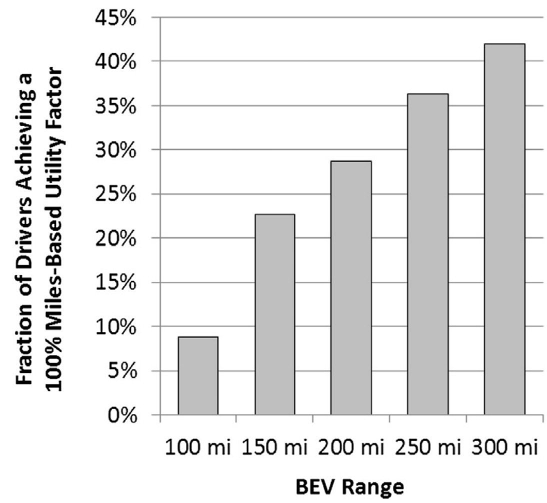

Fig. 3. Histogram of the fraction of TCS drivers completing all of their mileage as a function of BEV range.

calculated by dividing the maximum BEV-achieved VMT by the original VMT.

When reduced to the fleet level, this analysis predicts slightly higher mile-based utility factors than we observe from the NHTS data set for lower range BEVs, as seen in Table 1. This is to be expected in part, as the analysis of TCS data considers individual trips with opportunity home charging, whereas the NHTS analysis only considers miles traveled at the daily level. At ranges of 200 mi and greater, however, the discrepancy between the TCS and NHTS utility factor predictions are only marginal. This may imply that it is reasonable to assume the TCS data set is representative of the national driving habits for the purpose of this study.

Results at the individual driver level are presented in Fig. 2, showing that a large number of TCS drivers can complete more than 90% of their intended travel with a BEV with a range of 100 miles or greater. Once BEV range reaches 300 miles, we see that more than 70% of the TCS drivers can complete more than 90% of their intended travel.

In Fig. 3 we show results for the fraction of drivers that were able to complete all of their driving with a BEV of a given range. We find a significant increase in the number of these drivers is provided by increasing BEV range from 100 to 150 miles. As range increases above 150 miles, the number of 100% utility factor drivers continues to increase steadily up to 42% at 300 miles range.

While the NHTS data set does not provide information on individual drivers, and the TCS data set may not be nationally representative, together these data suggest a substantial market may exist for a 150 mile and greater range vehicles on the basis of achieving 100% utility. And although this is not the only factor that drives consumer choice, we do expect it to be a significant one.

2.2. Defining the vehicle platform

The USABC vehicle OEM members provided vehicle performance data across a number of timeframes, technology advancement scenarios, and vehicle platforms. Following preliminary analysis of these data, the workgroup elected the 2020 average technology forecast as a basis for our time frame and state of technology. A mid-size sedan was selected as the platform of interest, due to its combination of efficiency and broad market appeal. This selection provided us with the necessary baseline glider mass, aerodynamic coefficients, motor and power electronics cost and mass coefficients, fuel price projections, and other variables necessary for our task.

The remaining vehicle platform parameter in need of definition is the total vehicle mass, which we recognize affects many aspects of vehicle performance. The most important performance metrics for this target setting exercise – range, acceleration, and fuel costs – will be controlled and accounted for in the process that follows. For example, our battery energy target is calculated to provide a given vehicle range, our battery, motor, and electronics powers are set to provide a 9 s 0–60 mph acceleration time, and our battery cost is set to equalize the vehicle purchase price and 5 years of fuel of a CV and BEV. However, other factors such as handling, safety, etc. are not directly addressed. We could, therefore, require that our BEV be equal in mass to a comparable CV. While this would ensure that all aspects of BEV and CV performance are identical (aside from range), this may result in unrealistic targets for battery mass given the required energy content to achieve the specified range. Alternatively, it would require significant OEM investment to utilize advanced materials and designs that provide the required strength, but at a lower weight to strength ratio.

A review of several currently available BEVs that have comparable CVs in Table 2 reveals that today's BEVs are 20–37% heavier than their CV counterpart. This shows that vehicle mass can feasibly be increased by 37% on a mid-size sedan platform while maintaining acceptable handling and safety. Discussion with the OEMs within the workgroup led to the selection of an additional

Table 1
Comparison of fleet utility factors for NHTS and TCS data sets.

BEV range	NHTS fleet mile-based utility factor	TCS fleet mile-based utility factor
100 mi	68%	82%
150 mi	81%	86%
200 mi	87%	88%
250 mi	91%	90%
300 mi	93%	91%

Table 2
Comparison of presently produced BEV and CV vehicle masses.

CV	BEV	EPA-rated range	Mass factor
Mitsubishi i	Mitsubishi i-MiEV	62 mi	1.30
Ford Focus	Ford Focus	76 mi	1.23
Nissan Versa	Nissan Leaf	73 mi	1.37
Toyota RAV4	Toyota RAV4-EV	103 mi	1.20
Fiat 500	Fiat 500e	83 mi	1.25

5%–35% vehicle mass being worth of consideration. Defining total vehicle mass in this manner enables us to move directly to vehicle simulations, and in fact simplifies our effort of computing required battery energy and motor power, as will be described subsequently.

2.3. Motor power and battery energy

With the vehicle platform and total vehicle mass defined, we can now calculate the required motor power and battery energy to meet our 9 s 0–60 mph acceleration for a given range requirement. To do this, we employ an iterative process of adjusting motor power and simulating a wide-open-throttle condition using the NREL developed FASTSim [7] software. In these simulations, motor power is ramped linearly to the peak rating of the motor during the first 5 s of the acceleration event, replicating the response observed in today's production BEV's [8]. Once the proper motor size has been identified, we then simulate the HWY and UDDS drive cycles and compute vehicle efficiency for each. These two metrics are then combined and weighted per the Environmental Protection Agency's (EPA) previously employed approach to estimate 5-cycle vehicle efficiency from 2-cycle data [9]. Finally, battery energy is calculated by multiplying this value (in Wh mi^{-1}) by the specified range requirement.

2.4. Battery discharge and charge power

Battery discharge and charge power requirements are time dependent. Generally, the highest rates subjected to a battery by a BEV application are the shortest in duration. For example, a specific BEV may require its battery to be capable of 120 kW discharge, but must operate at this power for only a few seconds to enable the vehicle to reach 60 mph in a specified amount of time. Rarely does an OEM expect that a BEV would be subjected to such a large power request for significantly longer durations. However, the specific relation of required power magnitude and duration is unclear.

To quantify this relationship, we simulate three standard drive cycles (US06, HWY, and UDDS) and three non-standard cycles. The first two non-standard cycles are the only cycles that include grade information, and were recorded by NREL over a trip from the NREL facility in Golden, Colorado, to Vail, Colorado (N2V) and back again (V2N) [10]. The route, nearly identical in both directions, averages a 0.58% grade over the total 86.8 mile distance. The N2V trip averaged 55 mph over this route, while the return trip (V2N) averaged 53 mph. The third non-standard cycle, DRIVE, was constructed to represent actual driving habits recorded from 2154 real-worlds, 1–2 day vehicle records. The construction of this duty cycle is detailed in Refs. [11], where it has been shown to yield exceptionally accurate predictions of average fleet efficiency.

All of these cycles were processed identically to yield relations of required power magnitude and duration as follows: (1) define a dead band, (2) isolate individual events outside of the dead band, and (3) compute the duration and average power of each event. This process is illustrated graphically in Fig. 4 below. The dead band was defined by the average power observed during the simulated DRIVE cycle.

The results of this process are shown in Figs. 5 and 6 (discharge and charge, respectively) for a vehicle mass factor of 1.2. Overlaid on these charts are additional relevant boundaries the workgroup considered.

On discharge, an upper boundary of 120 kW is defined by the limitations of the motor and power electronics. Note that the battery is required to deliver 120 kW peaks, 10 kW above the 110 kW at-the-wheels rating of the motor and power electronics, to account for efficiency losses in these systems. This 120 kW peak power discharge must be sustained for 4 s, following a linear 5-s ramp

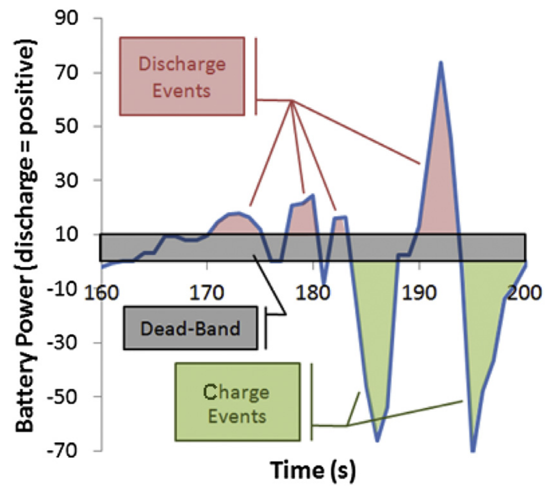

Fig. 4. Illustration of drive cycle processing for power requirements.

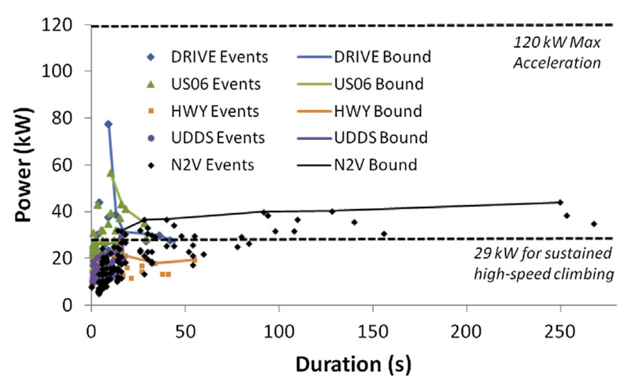

Fig. 5. Results of discharge power analysis for a 1.2 vehicle mass factor.

from 0 kW to enable the vehicle to successfully achieve its required 0–60 mph acceleration time of 9 s. A long duration "sustained hill climb" boundary of 29 kW was also identified and plotted. This was extracted from an exceptionally demanding segment of the V2N duty cycle simulation, where an average speed and grade of 64 mph and 2.3% were observed over a 25 min period. From the intermediate duration discharge pulses extracted from the drive cycles, we

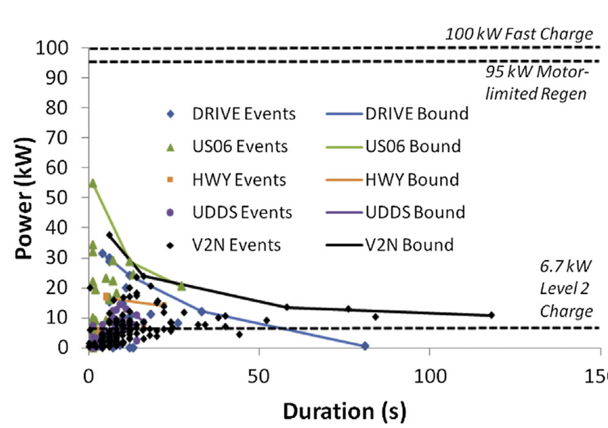

Fig. 6. Results of charge power analysis for a 1.2 vehicle mass factor.

find a 50 kW, 250 s discharge to be the most demanding criteria not already adequately addressed by these short and long term bounds.

For charge, we have multiple upper bounds to consider. Acknowledging that we would like to maximize our opportunities for regenerative braking, thereby improving the energy operation efficiency of the vehicle, we specify a motor limited charge power of 95 kW. Simulations show that this 95 kW regenerative braking charge power would need to be maintained for 6 s to bring the vehicle to a complete stop from 60 mph without use of friction brakes. At the low end of the magnitude spectrum, the battery must be capable of a sustained 6.7 kW (level 2) charge. A 12 s, 29 kW regenerative charge during the US06 cycle, and a 120 s, 11 kW regenerative charge during the V2N cycle completes the charging regime for the battery.

Alternatively, fast charge scenarios could dominate the battery charge power requirements. While many current fast chargers are typically sized to 50 kW, the workgroup envisioned an increase to 100 kW to support the larger batteries of future longer range BEVs. This would obviate the need for the motor limited, US06, and V2N derived requirements.

2.5. Battery volume and mass

Available battery volume was provided by the OEM workgroup members as 140 L for our mid-size sedan. Available battery mass, on the other hand, is determined by the defined total vehicle mass, the glider mass, and the motor and power electronics mass.

Calculation of glider mass begins with the baseline glider mass ($m_{g,0}$) selected for the vehicle platform. This was defined by subtracting the mass of the battery, motor, and power electronics ($m_{p,0}$) from total vehicle mass for our benchmark 2020 mid-size sedan. We then define a new glider mass (m_g) function (Eq. (1)) based on these parameters, our selected powertrain mass (m_p), and a 0.57 mass compounding factor taken from Ref. [12] to account for necessary changes in glider mass as the powertrain mass changes.

$$m_g = m_{g,0} + 0.57(m_p - m_{p,0}) \tag{1}$$

Next we calculate the available powertrain mass by subtracting m_g from total vehicle mass (m_{BEV}) and solving for m_p (Eq. (2)).

$$m_p = (m_{BEV} - m_{g,0} + 0.57m_{p,0})/1.57 \tag{2}$$

Finally, we calculate battery mass (m_{batt}) by subtracting the mass of the motor and power electronics from the powertrain mass (Eq. (3)).

$$m_{batt} = m_p - k_{mpe}P_{BEV} \tag{3}$$

Note that the result of this approach is the pack level mass, inclusive of all structural components, thermal management systems, disconnects, fuses, balancing electronics, etc.

2.6. Battery cost

To calculate allowable battery cost, we take a simplified approach based upon equating the MSRP of the BEV plus five years of electricity cost with that of the CV plus five years of gasoline cost (Eq. (4)). We define the MSRP of each vehicle as the cost for the glider and the powertrain, where the glider of each vehicle is equal in cost (Eqs. (5) and (6)). Fuel costs are calculated assuming 12,000 miles traveled per year for each vehicle, using Energy Information Administration price projections from 2020 to 2024, our calculated BEV efficiency (kWh mi), and the US DRIVE reported efficiency for the CV (Eqs. (7) and (8)). Combining these five equations and solving for the allowable battery cost yields Eq. (9).

$$\mathrm{MSRP}_{BEV} + C_{elec} = \mathrm{MSRP}_{CV} + C_{gas} \tag{4}$$

$$\mathrm{MSRP}_{BEV} = C_g + m \times (c_{mpe}P_{BEV} + C_{batt}) \tag{5}$$

$$\mathrm{MSRP}_{CV} = C_g + m \times (c_{CV1} + c_{CV2}P_{CV}) \tag{6}$$

$$C_{elec} = \mathrm{VMT} \times (c_{elec}\varepsilon_{BEV}) \tag{7}$$

$$C_{elec} = \mathrm{VMT} \times (c_{gas}\varepsilon_{CV}) \tag{8}$$

$$C_{batt} = (c_{CV1} + c_{CV2}P_{CV} - c_{mpe}P_{BEV}) + \mathrm{VMT} \times (c_{gas}\varepsilon_{CV} - c_{elec}\varepsilon_{BEV})/m \tag{9}$$

The results of this process yield the maximum pack-level cost that will equalize the 5 year operational cost of the BEV and CV prior to the application of the manufacturer-to-retail markup factor, *m*. It is thusly indicative of the price at which a vehicle OEM is expected to purchase the battery pack from its supplier.

2.7. Pack level, EOL analysis results

These calculations were performed for multiple vehicle ranges and mass factors. A subset of these results is presented for battery specific energy, energy density, and cost in Figs. 7–9 respectively. In all cases, these requirements become significantly more challenging as vehicle range is increased. With respect to vehicle mass factor, it is important to notice that while the specific energy requirement is relaxed as mass factor increases, the energy density and cost requirements become more demanding. This is because increasing the mass factor increases the required battery energy for a given range, but increases the battery mass budget more so.

2.8. Cell level, BOL requirements

As noted previously, this target analysis has been conducted to calculate pack level requirements. Further, our energy and power targets refer to available energy at EOL. Calculating beginning-of-life (BOL) cell level parameters, such as those which may be measured in early development phases or reported on a datasheet, requires consideration of battery pack balance of systems cost, mass, and volume values, degradation through life, and accessible state of charge windows. These values can change considerably

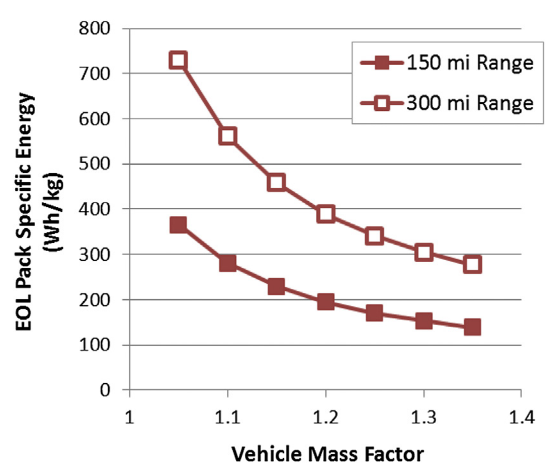

Fig. 7. Required EOL pack specific energy as a function of range and vehicle mass factor.

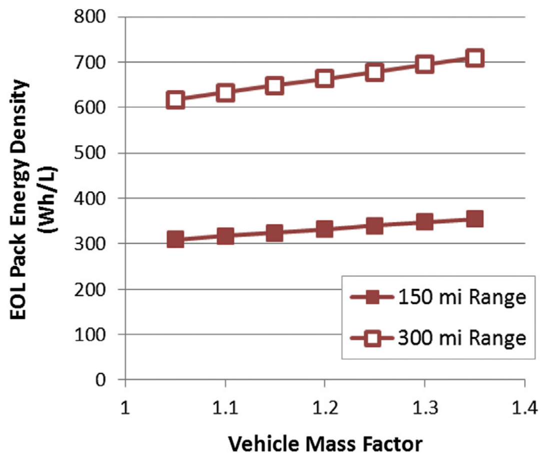

Fig. 8. Required EOL pack energy density as a function of range and vehicle mass factor.

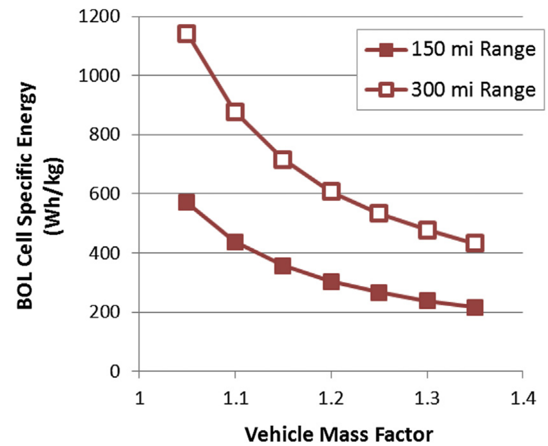

Fig. 10. Example BOL cell specific energy as a function of range and vehicle mass factor for assumed degradation of 20% and cell mass fraction of 80%.

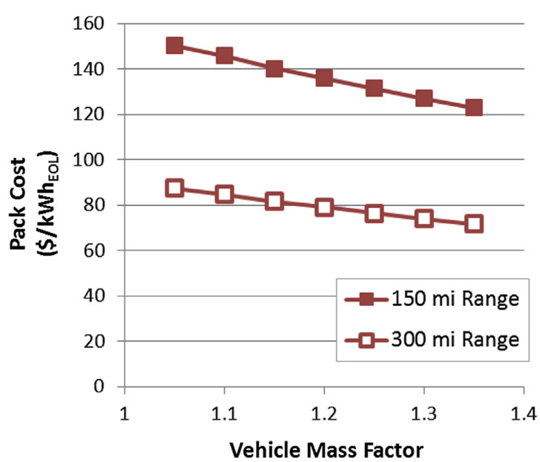

Fig. 9. Required pack cost as a function of range and vehicle mass factor.

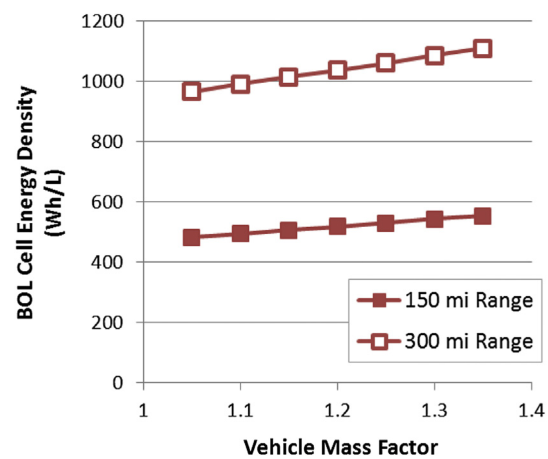

Fig. 11. Example BOL cell energy density as a function of range and vehicle mass factor for assumed degradation of 20% and cell volume fraction of 80%.

with cell chemistry, cell design, pack design, and operational conditions. As we have published end-of-life pack-level values herein, our targets are thus technology agnostic – indifferent to application specific pack design parameters, chemistry-specific degradation rates, etc. Providing targets as such allows technology developers to consider more options, and thus increases the likelihood of achieving these targets.

To illustrate the effect of these factors, however, we provide a simple example of translating targets to cell level 'datasheet' parameters. First, we assume that at end-of life, only 80% of the total remaining energy in the pack will be accessible. Next, we translate to cell level properties by assuming that the cells comprise 80% of pack mass, volume, and cost. Applying these translations to the data in Figs. 7–9 yields the results of Figs. 10–12. It is important to reiterate, however, that this is merely one example of possible cell level requirements. As noted above, the scaling values applied will, in practice, be specific to each chemistry and pack design.

3. USABC pack target summaries

Following the completion of this analysis, the USABC workgroup considered these results in tandem with other vehicle performance and consumer requirements. Their final selections are shown in Table 3.

While the USABC has not specified a particular vehicle platform, mass, or range associated with these values, it is illustrative to explore the implications of these battery performance targets. Simulation of these system-level battery performance metrics in

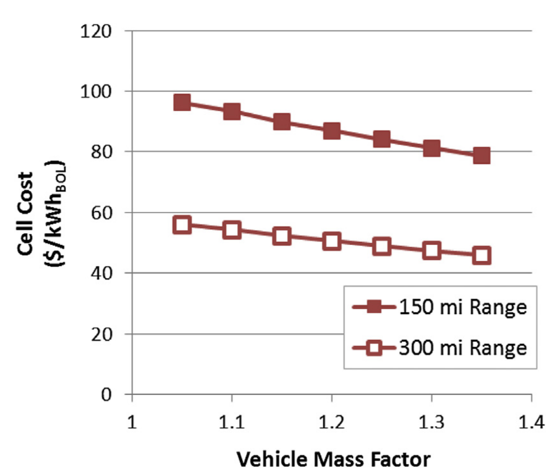

Fig. 12. Example cell cost as a function of range and vehicle mass factor for assumed degradation of 20% and cell cost fraction of 80%.

Table 3
USABC goals for advanced batteries for BEVs [13].

End of life characteristics at 30 °C	Units	System level	Cell level
Peak discharge power density, 30 s pulse	W L^{-1}	1000	1500
Peak specific discharge power, 30 s pulse	W kg^{-1}	470	700
Peak specific Regen Power, 10 s pulse	W kg^{-1}	200	300
Useable energy density @ C/3 discharge rate	Wh L^{-1}	500	750
Useable specific energy @ C/3 discharge rate	Wh kg^{-1}	235	350
Useable energy @ C/3 discharge rate	kWh	45	N/A
Calendar life	Years	15	15
DST cycle life	Cycles	1000	1000
Selling price @ 100 k units year^{-1}	% kWh^{-1}	125	100
Operating environment	°C	−30 to +52	−30 to +52
Normal recharge time	Hours	<7 h, J1772	<7 h, J1772
High rate charge	Minutes	80% ΔSOC in 15 min	80% ΔSOC in 15 min
Maximum operating voltage	V	420	N/A
Minimum operating voltage	V	220	N/A
Peak current, 30 s	A	400	400
Unassisted operating at low temperature	%	>70% Useable energy @ C/3 discharge rate at −20 °C	>70% Useable energy @ C/3 discharge rate at −20 °C
Survival temperature range, 24 hr	°C	−40 to +66	−40 to +66
Maximum self-discharge	% month^{-1}	<1	<1

the mid-size sedan used for this study implies a vehicle mass factor of 1.14, a 0–60 mph acceleration of 10.7 s, a total battery volume of 90 L, and the energy consumption and range values of Table 4. The acceleration value is notably slower than the 9 s 0–60 mph acceleration we applied; an increase in power density by ~20% is necessary to meet this mark. The implied total battery volume is also smaller than the 140 L employed herein, which would require a 36% lower energy density than specified in Table 3. Combined with our electricity consumption predictions, the battery cost is sufficiently low as to yield a simple 5 year CV-cost-competitiveness at as low as 9800 milesyear^{-1} of driving; or in as few as 4.2 years at 12,000 miles per year. These points may be indicative of intent for longer range vehicles and larger installed available energy, inaccuracy or outdating of assumptions applied to this analysis, or they may simply be the results of other factors beyond our scope impacting battery requirements.

4. Conclusions

Herein we have documented the analysis process that supported the selection of the USABC's updated BEV battery technology targets. Our technology agnostic approach identifies the necessary battery performance that will enable the vehicle level performance required of a commercially successful, mass market BEV, as guided by the workgroup's OEM members.

The result is an aggressive target, as targets should be. This implies that batteries need to advance considerably before BEVs can be both cost competitive with conventional vehicles and be a viable option for the mass market. It should be noted, though, that it does not mean BEVs cannot be successful today on a smaller scale by achieving a subset of the vehicle requirements demanded herein. For example, manufacturers have demonstrated the ability to build a 150+ mile vehicle, as well as a BEV within 20% of the mass of its CV counterpart, but the industry has yet to offer both elements together at a price capable of a 5 year payback for a 12,000 mile per year mass-market driver. It also remains to be seen what vehicle range will be achievable with today's vehicles following a 10+ year automotive life.

Table 4
Vehicle consumption and range with USABC battery targets.

	Consumption (kWh mi^{-1})	Range (mi)
UDDS	0.198	227
HWY	0.216	216
USSD + HWY	0.222	222
UDDS + HWY (adjusted)	0.289	156
US06	0.279	161

Acknowledgment

This study was supported by the Energy Storage, Vehicle Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy (Contract No. DE-AC36-08GO28308). The authors would specifically like to thank Dave Howell and Brian Cunningham of the U.S. Department of Energy for their continued guidance and support. The use of FASTSim, ADVISOR, and DRIVE computational tools, all developed at the National Renewable Energy Laboratory under funding from the U.S. Department of Energy's Vehicle Technologies Program, was critical to the completion of this study. Special thanks to Aaron Brooker, Eric Wood, and Adam Duran for supporting our use of FASTSim, ADVISOR, and DRIVE; Jeff Gonder for supporting the use and analysis of the drive data sources from NREL's Secure Data Transportation Center; and Ahmad Pesaran for his continual guidance.

Glossary

BEV	battery electric vehicle
BOL	beginning of life
CV	conventional vehicle
DOE	department of energy
EOL	end of life
NREL	national renewable energy laboratory
OEM	original equipment manufacturer
TCS	traffic choices study
USABC	United States Advanced Battery Consortium
VMT	vehicle miles traveled

Nomenclature

C_{batt}	manufacturing cost of battery
c_{CV1}	first cost coefficient of CV powertrain
c_{CV2}	first cost coefficient of CV powertrain
C_{elec}	total cost of electricity
c_{elec}	cost coefficient of electricity (\$ kWh^{-1})
C_g	manufacturing cost of glider
C_l	total cost of gasoline
c_{gas}	cost coefficient of gasoline (\$ gal^{-1})
C_{mpe}	motor and power electronics cost coefficient (\$ kW^{-1})
ε_{BEV}	efficiency of BEV (kWh mi^{-1})
ε_{CV}	efficiency of CV (gal mi^{-1})
k_{mpe}	motor and power electronics mass coefficient (kg kW^{-1})
M	manufacturer to retail markup factor
m_{batt}	battery mass
m_{BEV}	total BEV mass
$m_{g,0}$	baseline glider mass
m_g	glider mass
$m_{p,0}$	baseline drivetrain mass
m_p	BEV drivetrain (battery, motor, and power electronics) mass
$MSRP_{BEV}$	manufacturer suggested retail price of BEV
$MSRP_{CV}$	manufacturer Suggested Retail Price of CV

P_{BEV} BEV power (kW)
P_{CV} power of CV
VMT total vehicle miles travelled

References

[1] EV Everywhere Grand Challenge, (Online) Available from: http://www1.eere.energy.gov/vehiclesandfuels/electric_vehicles/index.html (accessed 25.11.2013).
[2] USABC Goals for Advanced Batteries for EVs, (Online) Available from: http://www.uscar.org/commands/files_download.php?files_id=27 (accessed 25.11.2013).
[3] Tony Markel, et al., J. Power Sources 110 (2002) 255–266.
[4] Transportation Secure Data Center, (Online) Available from: http://www.nrel.gov/vehiclesandfuels/secure_transportation_data.html (accessed: 25.11.2013).
[5] National Household Travel Survey, (Online) Available from: nhts.ornl.gov (accessed: 12.2.2010).
[6] Traffic Choices Study – Summary Report, Puget Sound Regional Council, April 2008.
[7] Future Automotive Systems Technology Simulator, (Online) Available from: http://www.nrel.gov/vehiclesandfuels/vsa/fastsim.html (accessed: 25.11.2013).
[8] Henning Lohse-Busch, Mike Duoba, Eric Rask, Mark Meyer, Advanced Powertrain Research Facility AVTA Nissan Leaf Testing and Analysis, Argonne National Laboratory, October 2012.
[9] http://www.gpo.gov/fdsys/pkg/FR-2011-07-06/html/2011-14291.htm (accessed 12.11.13).
[10] ibid 3.
[11] Jeremy Neubauer, Eric Wood, SAE Tech. Pap. (2013), http://dx.doi.org/10.4271/2013-01-1453, 2013-01-1453.
[12] Donald Malen, Kundan Reddy, Preliminary Vehicle Mass Estimation Using Empirical Subsystem Influence Coefficients, University of Michigan, May 2007.
[13] Development of Advanced High Performance Batteries for Electric Vehicle (EV) Applications: Request for Proposal Information (RFPI), Unites States Advanced Battery Consortium LLC, September 18, 2013.